



Development of a Shotcrete 3D-Printing (SC3DP) Technology for Additive Manufacturing of Reinforced Freeform Concrete Structures

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Abstract. In this paper, a novel Additive Manufacturing (AM) technique for robot-based fabrication of large-scale freeform reinforced concrete elements is presented. The AM technology, called Shotcrete 3D Printing (SC3DP), is based on an automated shotcreteing process and offers the ability to integrate structural reinforcement in both principal directions and enables printing of horizontal cantilevers onto vertical surfaces. Moreover, the SC3DP technique effectively addresses the problem of cold joints that is inherent to other 3D printing techniques. However, as controlling the process parameters of the SC3DP technique is significantly more complex than it is for conventional 3D concrete printing processes, several closed-loop online control routines were developed and integrated. The resulting gain of control for this adaptive fabrication process is demonstrated through a case study for the production of a complexes reinforced concrete component. Moreover, its conceptual implications are discussed and an outlook for future work is given.

Keywords: Robotic fabrication · Online path-planning
Concrete reinforcement · 3D printing · Shotcrete 3D printing

1 Introduction

In 2016 the Universities of Braunschweig, Clausthal and Hannover started an interdisciplinary research project on Additive Manufacturing (AM) with sprayed concrete. Six different institutes are working on the development of a new AM method, which has the potential to produce large scale, reinforced concrete elements with a high surface accuracy, based on the principals of shotcrete technology. The research activities are consolidated in a novel large scale a robotic research facility the “Digital Building Fabrication Laboratory” (DBFL) for additive and subtractive manufacturing of reinforced freeform concrete structures [1].

This paper presents the ongoing research on Shotcrete 3D Printing (SC3DP), which is currently being carried out on the DBFL. The SC3DP technology has the potential of producing structural freeform concrete elements with large overhangs and a high

surface quality. The paper focuses on offline path planning based on experimental knowledge and the development of control algorithms for the AM process. In particular, a sensor guided online path planning technology for SC3DP is presented since model-based offline planning alone could not achieve high component accuracies.

1.1 Additive Manufacturing with Concrete

Although several AM technologies are used in the manufacturing industry today [2], the research for construction scale 3D printing is focusing on two different technologies: Firstly, powder bed printing [3] and secondly extrusion based methods. The extrusion based AM-methods are the most common in research and are about to be used in industrial applications. The first viable approach of large-scale concrete printing was made by Behrokh Khoshnevis with “Contour Crafting” (CC) [4]. Based on the extrusion of viscous-like materials layer-by-layer to build-up a 3D object. Two trowels attached to the printing nozzle are used to achieve a smooth and accurate planar surface. Another extrusion based process is the “Concrete Printing” technology developed at the Loughborough University [5]. Unlike CC, no trowel is used, therefore the resolution needs to be smaller to achieve the required accuracy. Both projects show the great potential of AM technologies in the building industry. Another AM approach has been made at the ETH in Zurich with the project “mesh mold” [6]. Instead of AM manufacturing the concrete element, a rebar formwork, is manufactured by a robot and gets filled with concrete afterwards, which allows the production of non-standard elements with a fully functional structural reinforcement. Nevertheless, there are still major challenges for AM of structural reinforced concrete, such as implementation of reinforcement, surface quality and the cold joint problem [7]. Therefore, further research on AM with concrete is still necessary.

1.2 Potential of Shotcrete 3D Printing as an Additive Manufacturing Technique

The shotcrete technology has been around for more than 100 years and is mainly used in tunnel construction and mining industry [8]. It is fast and easy to apply on all kind of surfaces and allows the integration of reinforcement even with nonstandard geometries. The manufacturable complexity can be seen in projects like the Taichung opera house of Toyo Ito, which has been completed in 2016. The quality and accuracy of the process is highly depending on the skills and experience of the operator. The nozzle operator can adjust the strategy of material application according to the environment parameters in order to fill holes, avoid nesting or to avoid slipping of the applied material.

Compared to the established extrusion-based material application processes [6], spraying concrete offers several different advantages. It is possible to spray the concrete not only as horizontal layer (Fig. 1a), the material can also be placed laminar (Fig. 1b) on surfaces with altering orientations (Fig. 1c). By introducing additional accelerator, the time of solidification can be adjusted. This not only allows to print overhangs up to 90° (Fig. 1d), it reveals new possibilities to manufacture complex 3-dimensional concrete components. Using different amounts of the accelerator the curing process of

the material can be adjusted to offer support for upcoming layers or to be workable for additional post processing (Fig. 1e). Therefore, the material for the application process is being further developed at the TU Braunschweig together with industrial Partners. Additionally, the flexibility of the spraying process enables the integration of reinforcements into the production process, since it is possible to inject them during manufacturing of the component (Fig. 1f). Another unique feature is the reduction of cold joints, due to the impact energy of the shotcrete and the resulting geometrical interlocking of the layers. In conclusion, SC3DP offers the potential to address several disadvantages of existing AM technologies for manufacturing of freeform concrete elements.

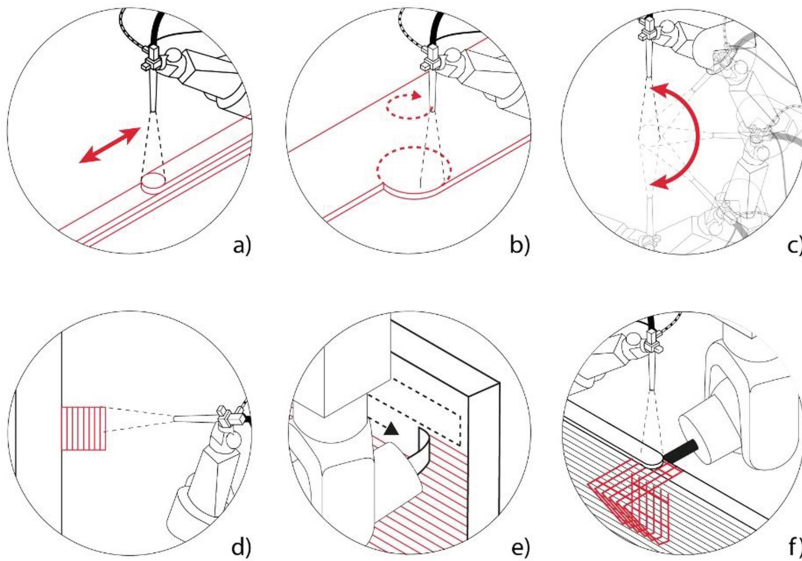


Fig. 1. Specific features of the SC3DP process: layer-by-layer application (a), laminar application (b), Variation of the application angle from 0° to 180° (c), overhang spraying (d), several post processing options (e), implementations of reinforcement and build-in-parts (f)

1.3 Challenges of Shotcrete 3D Printing

The application of sprayed concrete for AM of concrete components is a major challenge, as a large number of process parameters have to be kept in a constant ratio in order to achieve a homogeneous concrete application and therefore an acceptable part accuracy. The accuracy depends on parameters such as the concrete volume flow rate, the delivery pressure, the air volume flow rate, the air pressure, the concrete accelerator dosage and parameters related to the path planning such as the nozzle distance, velocities, layer spacing, application angle or times between layer applications. The variation of these parameters has a great influence on the associated target values, such as early strength, layer thickness, concrete quality (e.g. compressive strength, tensile

strength) and rebound. In particular, the early strength and the layer thickness pose a major challenge for additive production. The early strength results in a limited time window in which a next layer of concrete can be applied. If this time window is missed, the concrete is either too soft or already too hard. In the first case, material displacement occurs due to the high air pressure from the nozzle. In the second case, the concrete quality suffers from a lack of adhesion between the layers. A constant width of the application layers is also important for AM, so that the planned paths lead to the desired component. In conclusion, a good accuracy of the component is difficult to achieve in Shotcrete 3D printing due to various disturbances such as uneven concrete mixtures, fluctuating pressures in the supply hoses or suboptimal path parameters.

2 Offline Process Control Based on Experimental Knowledge

Parameter studies were conducted in order to identify appropriate spraying parameters for offline process planning. Therefore, it was mandatory to keep as many parameters as steady as possible to be able to find the adequate process parameters and to understand its influence on the outcome. Environmental conditions (e.g. temperature and humidity) cannot be controlled in an appropriate manner, but still have a great influence on the concrete behavior. Examinations on the flow spread were used to adapt the mixture to ensure a repeatable material behavior. The conveyance line of the concrete air can be an influencing parameter as well. Hose length, diameter and curvature have to stay the same for a consistent result. While the length and the diameter are easy to fix, the curvature is constantly changing due to the moving robot. Closed-loop controls for the material supply were used to compensate such disturbances (see Sect. 3.3). The main influencing parameters, which have been tested, are the nozzle distance, material deposition rate, flow of the compressed air and application speed. The results of the parameter studies have shown that the deposition rate and the application speed have nearly linear dependencies on the layer thickness. The spraying distance on the other hand has a linear dependency on the layer width. However, the air flow also has a major influence on the material distribution and therefore the layer geometry and the resulting rebound. Since this influence is not linear it is therefore considered as a constant parameter for offline process planning. Next to the parameter studies, several strategies, for manufacturing of concrete elements have been investigated. These experiments were used to develop algorithms for offline path planning to generate the robot motion for the production of the components (Fig. 2) [14]. The challenge here is to synchronize the material behavior and the results of the parameter studies with the robot movement. This challenge will be explained in more detail using the example of building a thin, curved concrete wall.

The first printed wall elements were single line elements, in which the shape was created by spraying layer on layer back and forth. The first results turned out to be promising. The used concrete, allowed the production of elements up to 100 cm height without the introduction of additional accelerator. However, one major problem turned out to be sagging on unsupported edges. On 90° corners the sagging is negligible (Fig. 2a), on a 180° turn (Fig. 2b) the sagging of the material increased with every single layer which made the production of precise components impossible (Fig. 3a).

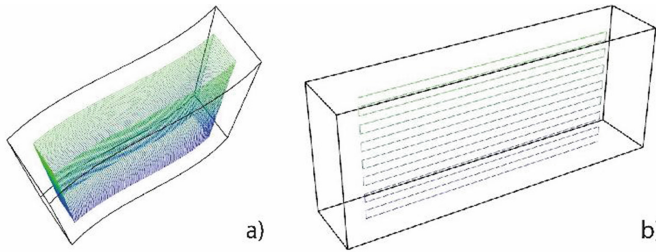


Fig. 2. Path planning for continues application ($>90^\circ$ corners) (a) and single line application (b)



Fig. 3. Sacking on unsupported edges (180° turns)

Avoiding 90-degree turns, would lead to extremely limited application strategies, and concrete elements could only be manufactured with a minimum thickness of at least twice the layer width. This would pose a major disadvantage for SC3DP since a single layer width is already wider than established application techniques. In order to build up a wall with the thinnest width possible, it is necessary to overcome the limitations of the “edge-sacking”. Experiments have shown, that decreasing the application speed towards the edges counteracts upcoming sagging. Additional material needed, can be applied in order to compensate for a deviation from the initial programmed (offline) target geometry. However, this behavior is highly dependent on the individual component geometry and cannot be predicted without complex simulations. Such experiences have led to the insight that adaptive processes based on measurement technology for the detection of geometric inaccuracies are essential in order to develop a reliable AM process.

3 Online Measurement and Process Control for SC3DP

The results of the presented experiments demonstrate the need for online measurement and control of the component geometry. The adjustment of the robot velocity as well as the distance between the surface and the nozzle has been identified as a suitable method

to avoid inaccuracies of the component geometry such as edge-sacking or material displacement. An online velocity control, which regulates the layer thickness, can also counterbalance disturbances of the material supply e.g. failures in the conveyer system or can be used as a controlled process for introducing additional elements, like reinforcement or other in-built-parts. To be able to realize such a closed-loop control system, a measurement technique is required that can be used for online measurement of the deviations from the desired shape. Therefore, the State-of-the-Art for control systems for layer-based Additive manufacturing serves as a basis for the selection of suitable measuring and control methods.

3.1 Measurement and Control Concepts for Layer-Based Additive Manufacturing

The lack of quality assurance in AM is an important technological barrier that prevents AM to be used for industrial production. [13] In all AM technologies, disturbances (e.g. material inconsistency) or environmental influences (e.g. variations in temperatures) lead to inconsistent component qualities. In contrast to the established subtractive processes, where in-process monitoring is common today, additive technologies have not yet established standardized online process monitoring to detect discontinuities during manufacturing. However, research is currently focusing increasingly on approaches that enable the online detection of inaccuracies and their compensation using adaptive processes. In particular, adaptive technologies for layer-based additive processes are of interest for the transferability to additive production with sprayed concrete. Heralić et al. [9] developed an in-situ monitoring technology for laser deposition welding based on a 3D laser scanner. The team was able to prove that 3D sensor data can be used for in-process detection of disturbances and their compensation. For this purpose, a control algorithm was developed using an iterative learning approach that incorporates the 3D data to adjust the layer height during the process in order to avoid geometric inaccuracies. Xiong et al. [11] developed a vision sensor system and a process controller for AM with gas metal arc welding (GMAW). The system uses a CCD camera to monitor the distance between the nozzle and the surface. A control system was implemented, that uses the nozzle distance as input to adjust the deposition rate to control the layer height in closed-loop. Holzmond et al. [12] developed a system based on 3D digital image correlation as in-situ measurement technology for monitoring the surface geometry in fused deposition modeling (FDM). The system uses stereoscopy to capture 3D point cloud data of the printed geometry. The 3D point cloud data is then compared with the digital CAD model to detect manufacturing errors. Wolfs et al. developed a height measurement and feedback system for 3D concrete printing [10]. The system utilizes a 1D Time-of-Flight (TOF) distance sensor to measure the distance between the nozzle and the surface for closed-loop control of the nozzle position. The results from the State-of-the-Art indicate that in-situ measurement can be utilized to increase the component quality in layer-based AM. Nevertheless, the results also emphasize the advantages and disadvantages of the different measuring technologies. For example control approaches based on 2D cameras are limited for measuring the distance between nozzle and surface, concepts based on 3D measurement and point cloud data require constant ambient conditions

and laser triangulation is limited to measuring 2D profiles. The development of a control concept for additive concrete spraying therefore requires a proper evaluation of the different measuring technologies.

3.2 Online Geometry Measuring for Shotcrete 3D Printing

In order to select a measuring technology for closed-loop control of the component geometry, laser triangulation was compared with the TOF. In-process measurements of both principles were carried out and compared with each other. The results show that the disturbing influences of the spraying process, especially the rebound, results in insufficient measuring stability for the TOF camera. The results of the laser sensor, on the other hand, exceeded the expectations. Here it was possible to get appropriate measuring results even with the spray-jet between the CCD camera and the laser line. Laser triangulation may have the disadvantage of only being able to update a 2D section of the component and not an entire area. However, this disadvantage is compensated by the higher precision and the robust measuring process. Therefore, laser triangulation was chosen for implementation of the control concept in this project (Fig. 4).

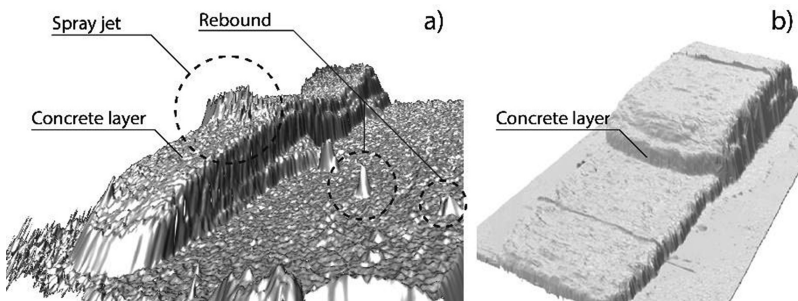


Fig. 4. Online measuring for Shotcrete 3D Printing (a) Time-of-Flight and (b) laser triangulation

3.3 Control Concept for Shotcrete 3D Printing and Experimental Implementation

Compared to conventional extrusion technique for additive manufacturing with concrete the SC3DP method is influenced by a larger number of process parameters, which have to be kept in a constant relation to produce high quality components. In order to allow comprehensible results of the parameter studies, it was decided, to keep as many parameters as steady as possible. Therefore, all process parameters for the material supply, which are directly measurable (e.g. flow rate of the compressed air) have been included in separate close-loop controls (see Fig. 5) to compensate for disturbances “D”. This multi-loop control approach was chosen due to its reasonable implementation effort. It turned out that the influence of the process parameters among each other are neglectable and therefore it can be expected that a multi-variable control approach would not yield significant improvements.

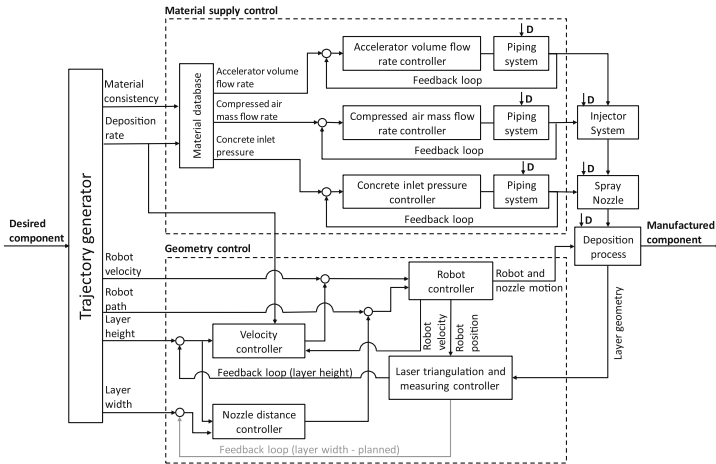


Fig. 5. Implemented control concept for Shotcrete 3D Printing (left) and online measuring using a laser triangulation sensor (right)

All controllers are implemented using a Beckhoff control system. The current control concept uses a “Trajectory generator” that generates the time-dependent and offline planned variables for the different controllers. This includes the desired material consistency and deposition rate, the robot path and velocity and the geometry of the deposition layers. To reduce the offline planning effort for the material supply a “Material database” with the experimental knowledge of the parameter studies is used to define the set points for the closed-loop controller. The path of the robot is generated from CAD data and is then continuously sent to the “Robot controller” of the DBFL that is run by a Siemens Sinumerik 840D. A Stemmer C5 laser triangulation sensor is used to measure the component geometry while the concrete is applied. The sensor data is processed and synchronized with the current robot position to enable measuring in six dimensions using the “Laser triangulation and measuring controller”.

The geometry of the deposition layer (width & height) has been included in two additional control algorithms to compensate for geometric inaccuracies (e.g. material displacement). For the development of these controllers, the approaches presented in the state of the art were adapted for Shotcrete 3D printing (see Sect. 3.1). The first control algorithm uses the deviation between the planned and the actual layer height as well as the planned deposition rate to calculate a velocity offset for the robot. The “Velocity controller” not only ensures a constant layer height of the deposition process, it also enables an adaptive material deposition process to fill gaps or holes and to avoid material accumulations. The second controller leverages the distance between the nozzle and the surface to control the layer width. The “Nozzle distance controller” therefore ensures a constant distance between the nozzle and surface depending on the desired layer width. The controller utilizes the deviation between the planned and the actual layer height to calculate a correction vector for the robot path to control the nozzle distance. However, this only allows indirect control of the layer width.

Therefore, it is planned to measure the layer width additionally in order to enable direct closed-loop control of the layer width in the future.

The control concept is currently being examined in the DBFL. Figure 6 shows the first results of an experimental investigation of the control algorithms to compensate for irregularities. Therefore, a hole was inserted manually during the production of a straight wall and the system's reaction to this geometric inaccuracy was observed. It can be seen that the algorithm is able to compensate the geometric error in a few deposition layers. However, further parameter studies are still required to optimize the controller parameters e.g. to increase the robustness and to accelerate the control process.

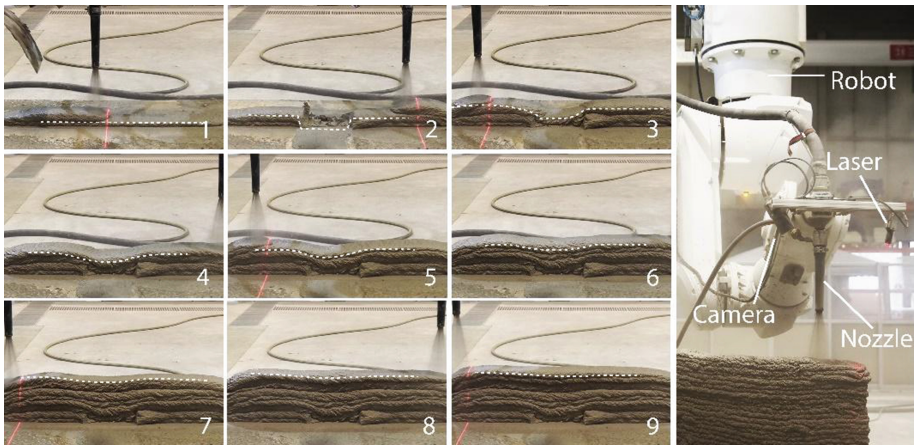


Fig. 6. Online measurement and closed-loop control for manufacturing of a straight wall

4 Case Study: Multidirectional Printing and Introducing of Reinforcement

In order to investigate the full potential of SC3DP a case study has been designed, combining all previous mentioned features. The build-up strategy is a combination of a horizontal layering, vertical application, introduction of reinforcement and a 90° overhang. As first production step, a single wall is produced with horizontal layering, as described in Sect. 2. The single wall element functions as a “backbone” (Fig. 7a) which is used as a base for upcoming vertical applications. One side of the wall element is straight and the other side is curved. The produced wall element had a height of 1 m and a width of 1.40 m. Pre-bend steel rebars have been manually placed in between the application of the horizontal layer (Fig. 7b). Afterwards vertically spraying with an average thickness of approximately 20 mm was used to cover the side of the wall (Fig. 7c). The applied concrete has been sprayed with no additional accelerator, which allowed additional post-processing. Prefabricated reinforcement, in this case a carbon fibre fabric, has been placed in the still workable concrete (Fig. 7d). An additional

20 mm layer of concrete was applied to cover the fabric (Fig. 7e). This final layer has been manually smoothed, in order to create an even surface finish. As a final step, a console has been manufactured by spraying vertical layers, cantilevering from the vertical surface (Fig. 7f). The use of accelerator and the supported by the rebar enabled the production of a cantilever of 17 cm. The results indicate that even bigger overhangs are possible to produce, depending on the shape, curing time and additional support.

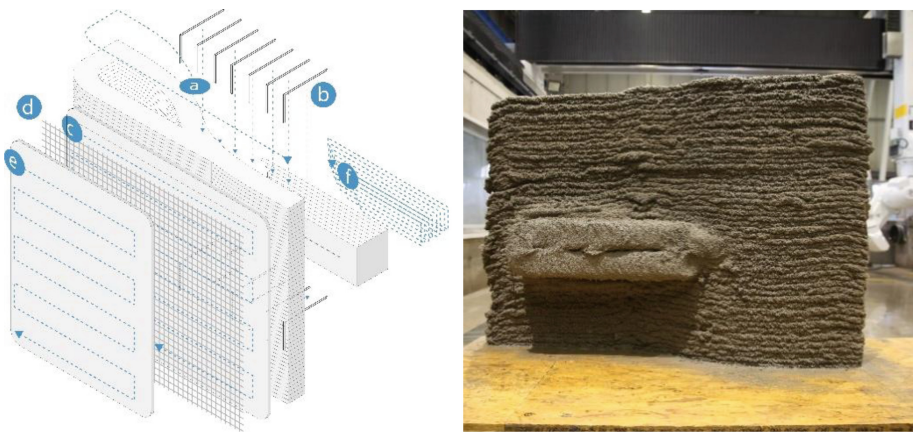


Fig. 7. Offline planning (left) and manufacturing result (right) of a complex reinforced concrete component produced by Shotcrete 3D Printing

5 Conclusion

The results of the experiments and case studies carried out have shown, for the first time, that complex concrete geometries with large overhangs and integrated reinforcement are possible to produce using Shotcrete 3D Printing. The experimental knowledge from several parameter studies can be used for an efficient offline process planning for the complex production processes. However, the results also led to the insight that high component accuracy is hard to achieve with model-based offline planning alone. Therefore, a multi-loop control concept for SC3DP has been developed that enables compensation of inaccuracies and thus precise production of the concrete components. The developed controller integrates a novel 3D measuring based compensation approach for in-process control of the component geometry. This has significantly increased the robustness of the production process especially with regard to material displacements. Production defects that previously led to wasted parts can now be avoided.

However, further developments are necessary in order to industrialize the manufacturing process. On the one hand, an automated post-process for the surface has to be developed to compensate for the very rough surface quality of the additive process. On the other hand, further parameter studies have to be carried out to examine the limits of the process (e.g. overhangs). Additionally process chains for the automated integration

of reinforcement and prefabricated components (e.g. empty conduits) have to be developed. A major disadvantage of the laser triangulation system is currently the use of a single laser line. With the current system, it is only possible to measure before or after the spray jet, which limits the use of the geometry controller for only one direction of movement. Additionally the geometric freedom for robots paths is limited in due to shaded areas in narrow radii (e.g. sharp corners). It is therefore planned to equip the system with three laser lines, which will be positioned in a triangle around the spray jet. In addition, the control algorithm for adjusting the nozzle distance will be extended with a close loop-control for the layer width to further increase the accuracy of the manufacturing process. Since the laser system can also be used to measure the entire component, it is planned to use the 3D data, for generating a robotic paths for further post-processing (e.g. smoothing or subtractive post-processing).

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